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Towards a domain-based framework for use of rainfall forecasts in control of integrated urban wastewater systems

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Abstract: An increasing number of Model Predictive Control (MPC) tools have recently been developed. These MPC methods utilize as input a wide range of rainfall forecasts, which differ in their characteristics and prediction skills. Operators need to identify the most appropriate MPC and rainfall forecast for their needs. A domain-based framework is proposed to distinguish between four operational domains, which consider the magnitude of the forecasted rain and the expected status of the system. The framework is presented by using selected Danish case studies as examples, and it will provide a support to operators in the implementation of MPC strategies.

Keywords: Model Predictive Control, uncertainty, multi objective optimization, Water Smart Cities

INTRODUCTION

The improvement in the techniques to forecast rainfall in urban areas is creating new opportunities for operators of urban wastewater infrastructure. Information on the future evolution of rainfall can be used to operate the different parts of the integrated urban wastewater system (sewer and treatment plant) in a more efficient way and/or to warn users and citizens about malfunctioning (e.g. flooding, loss of bathing water quality). Specifically, in Denmark, recent research developments (e.g. Mikkelsen et al., 2013) have focused on new techniques to integrate rainfall-runoff forecasts (both short and long term - Courdent et al., 2016; Thorndahl et al., 2013), uncertainty estimation methods (e.g. Löwe et al., 2016) and control strategies (e.g. Vezzaro and Grum, 2014). The initial focus on reduction of Combined Sewer Overflows (CSO) and better operation of Waste Water Treatment Plants (WWTP) in wet weather periods has now been extended to other operation domains, such as energy-based optimization in dry weather (Bjerg et al., 2015; Jørgensen et al., 2017) flood warning (Hellmers et al., 2016; Meneses et al., 2015), and maintenance planning.

Rainfall forecasts are generated by using different techniques, which range from extrapolation of radar measurements (Thorndahl et al., 2017) to complex Numerical Weather Prediction (NWP) models, or a combination thereof. Each different forecast product has different characteristics and uncertainty. Rainfall forecasts can be used in different ways by operators. For example, forecasted rainfall and runoff can be used to select different rule-based control schemes, or they can be used as input to Model Predictive Control (MPC) strategies, which can utilize different objective functions to optimize the operation of the system. While national meteorological institutes and international centres are traditionally the main suppliers of rainfall forecasts, an increasing number of private companies are offering rainfall forecast products on the market (see ForecastWatch, 2016).

Operators are faced with a range of newly developed MPC strategies and they need to identify the most appropriate forecasts for their needs. For example, an analysis of the spatial resolution is necessary for MPC aiming at reducing CSO volumes, optimizing wet weather WWTP operations and warning about flooding risk. Long term forecasts are typically generated with course temporal resolution on grids with cells that are several kilometres in size, i.e. only a handful of forecast cells can be available for medium-small urban catchments. Conversely, radar-based forecasts have both high spatial and temporal resolution (hundred meters and few minutes, respectively), making them appropriate for e.g. prediction of WWTP inflow. However, their short forecast horizon makes them unfitted for managing storage volumes in large urban drainage systems, where emptying of detention basins and network transport times are usually in the order of several hours. Forecast uncertainty is also a factor which needs to be considered by operators. False alarms and missed events may e.g. result in increased damages (e.g. if flooding is not forecasted) and additional financial and environmental costs (e.g. if a modification of WWTP operations leads to a worsening of its performance), which may eventually undermine the operators' trust in the MPC strategy.

This work proposes a preliminary framework for identifying different operational domains where rainfall forecasts can be used for operating the integrated urban wastewater infrastructure. By using some recent examples as the starting point, we propose a scheme which can help researchers, practitioners and operators to (i) illustrate the existing options for optimization of their systems, to (ii) link these options to characteristics of available rainfall forecasts, to (iii) improve communication (hindered by the great number of available options for forecast inputs and control strategies) and thereby facilitate the implementation of advanced control strategies, and to (iv) identify new applications, possibilities and research gaps. This framework will be further developed during the Water Smart Cities project (www.watersmartcities.ennv.org) over the next three years.

METHODOLOGY

The proposed framework is based on the analysis of selected case studies where MPC of integrated urban wastewater systems has been developed, including simulation studies, pilot studies, and full scale implementations. These investigated systems include Danish catchments where the Water Smart Cities partners are involved in the development of new MPC strategies. Information from the scientific literature has been used to put these cases into an international perspective.

The rainfall forecasts employed in each case study were classified based on their main characteristics. After numerous dialogues with the operators in the major water utilities in Denmark, we identified the main *operational domains* where MPC is currently applied, which then provide the basis for the proposed forecasts.

Characterization of rainfall forecasts

The different available rainfall forecasts can be described in terms of spatial and temporal resolution, forecast horizons, and update frequency (see Table 1).

- *Grid spatial resolution* defines the distance size of each grid cell of the forecast model. To assess the suitability for MPC of integrated urban wastewater systems where rainfall spatial heterogeneity can play an important role, the grid resolution should ideally be smaller than the size of the catchment (Schilling, 1991).
- *Time resolution* defines the time intervals for which forecasts are available. High time resolutions (in the range of minutes) are needed for small systems, characterized by short response times, and for prediction of highly dynamic processes (such as flooding).
- *Forecast horizon* describes the future period covered by the forecasts, which depends on the technique used to generate the forecasts. The suitability for MPC applications should be evaluated according to the size of the system and the dynamics of the controlled process (e.g. emptying of detention basins or changing to wet-weather operation mode for at WWTP).

- *Forecast update frequency* defines the interval when a new forecast, based on the latest available information, becomes available. While a high forecast update frequency is preferable for MPC of integrated urban wastewater systems, the latest forecast does not necessarily provide the best accuracy (cf. the discussion in Pappenberger et al., 2011), requiring the inclusion of information from earlier forecasts (e.g. Mittermaier, 2007).

Rainfall forecasts are affected by uncertainty, originating both from measurements and model structural uncertainty. Methods for including this uncertainty into MPC have been developed (e.g. Maestre et al., 2013; Vezzaro and Grum, 2014), and in the implementation phase it should be ensured harmonization between how uncertainty is expressed in the forecasts and in the MPC. For example, the forecast uncertainty is usually expressed by using ensembles, while DORA control strategy (Vezzaro and Grum, 2014) uses a probabilistic uncertainty description of runoff flows.

Case studies

CSO reduction. This includes the most widespread MPC application in the field of urban drainage. In the Danish context, applications range from the city of Aarhus, where a MPC using radar-based forecasts to reduce overflow volumes is under implementation (Halvgaard and Falk, 2017), to the city of Copenhagen, where the potential for application of a control strategy considering forecast uncertainty and sensitivity of the receiving water body was investigated by Löwe et al. (2016) and Vezzaro et al. (2013), respectively. The available storage volume (detention basins, pipes) is controlled by the MPC based on the expected runoff flows and volumes in the different subcatchments.

Energy-based optimization. In the Kolding case study presented by Jørgensen et al. (2017) and Bjerg et al. (2015), WWTP operations are integrated in a Smart-Grid concept, i.e. MPC aims at operating the most energy consuming operations (aeration and pumping) during periods when energy prices are lower. The wastewater is stored in the sewer pipes upstream the WWTP during high-electricity price periods and it is pumped to the plant and treated when prices are lower.

WWTP inlet load optimization. Several examples of integrated strategies aiming at reducing the impacts from the sewer system on the WWTP operation can be found in literature (e.g. Seggelke et al., 2013).The example described in Tik et al. (2015a,b) also considers emptying of detention basins after a rain event: the optimized emptying strategy aims at reducing the WWTP inlet TSS peaks, improving the WWTP performance. A similar approach, aiming at developing an emptying strategy which will minimize WWTP overload will be developed for the Damhusåen catchment (described in Courdent et al., 2016a) during the Water Smart Cities project.

Flood warning In the Copenhagen case study presented by Meneses et al. (2015), forecasts based on a combination of NWP models and radar measurements are used as input for a detailed 1D-2D hydrodynamic model to generate flooding maps across the city. Whenever the predicted water level on the surface exceeds a predefined threshold, a warning is sent. A similar system, employing radar-based forecasts, has been described in by Einfalt et al. (2016) and Hellmers et al. (2016) for the German cities of Lubeck and Hamburg.

Table 1. Overview of main characteristics for rainfall forecast methods currently employed by the major Danish water utilities.

	Radar	**Merged NWP-radar**	**NWP**
Grid spatial resolution	Hundred meters	~Kilometres	~Kilometres
Time resolution	1 Minute[a]	10 Minutes	~hours
Forecast horizon	2-3 hours	6-8 hours	48 hrs
Forecast update frequency	10 minutes	1 hour	6 hours

[a] after interpolation of radar measurements (available every 10 minutes)

RESULTS AND DISCUSSION

Operational Domains

After numerous dialogues with the operators in the major water utilities in Denmark, we propose a framework to better distinguish the operational domains in which rainfall forecasts can be used to better operate integrated urban wastewater systems (Figure 1). The four operational domains outlined below involve evaluation of two aspects: a weather forecast and the current status of a catchment's storage capacity. The domains require different horizons, and they are therefore linked to different typologies of rainfall forecasts.

Dry weather – empty storage. Integrated wastewater systems are usually operating in dry weather (conveyance and treatment of wastewater), but rainfall forecasts can also benefit control strategies operating in these periods. Energy-based optimization control operates only in dry weather (as in the Kolding example) and it uses the combined sewer infrastructure in a way outside its original design purpose (i.e. wastewater is kept in the system, while the sewer were designed to convey the mix of storm- and wastewater away from the urban area in the most effective manner). Nevertheless, the full storage capacity of the drainage system should be available for flooding and CSO reduction (i.e. the urban drainage infrastructure should be able to switch back to its original design function) whenever a rainfall event is expected to hit the controlled catchment. In this perspective, long-term rainfall forecasts can be used to switch between the dry and wet weather domains in due time. In fact, the forecast horizon should be sufficiently long to allow emptying of all the available storage, to ensure that all the stored wastewater has left the system and it is treated at the WWTP before the rain events starts. In this domain it is essential to correctly predict the state of the future weather (dry/wet), with little need for volume information. The forecasts are in fact only used to distinguish between states of the systems (dry/wet), i.e. if the expected rain event is above/below a threshold (Courdent et al., 2016a, 2016b). For this application, NWP forecasts can be sufficient both in terms of forecast horizon and volume accuracy. Some NWP products have a forecast horizon up to 15 days (with a coarse temporal resolution of few hours - e.g. ECMWF, 2015), which makes them suitable for planning maintenance activities.

Dry weather - with stored runoff. This domain includes control strategies operating after a rainfall event, such as the emptying strategies to optimize the WWTP inlet loads. This domain consider the transition from the original sewer function (conveying storm- wastewater away) to the dry weather operation (storing wastewater to optimize WWTP energy consumption; reduction in pump wearing, etc.), with a specific focus on the WWTP performance. Similarly to the previous dry domain, the needed volume accuracy is low, since the main focus is to correctly predict the change between the dry/wet states within the emptying time of the system. However, since the stored volumes of storm-wastewater are usually greater than the wastewater volumes managed by dry weather controls, it is necessary to modify the threshold between the dry/wet domain. In fact, a small event (which would not trigger the wet domain when operating the network in dry weather) might increase the CSO/flooding risk when the available storage volume due to a previous big rain event. The forecast horizon should be of the same magnitude of the emptying time of the system, requiring the utilization of NWP models or mixed (NWP and radar) forecasts.

Wet weather - within design capacity. This domain includes MPC ranging from forecasting inflow to WWTP (and thereby switching to wet-weather operation) to MPC of the sewer network to reduce CSO risks and – when these are unavoidable – their impacts. These controls require good prediction of runoff flows and volumes, i.e. a good accuracy of rainfall predictions is needed. Given the inherent uncertainties affecting the rainfall forecasts, a realistic uncertainty description can contribute to fully exploit the benefit of using forecasts (e.g. Vezzaro et al., 2014). Radar based forecasts are the most suitable for this operational domain, both in terms of spatial and temporal resolution and forecast update frequency. These characteristics allow for accurate estimations of runoff flows and also account for rainfall spatial heterogeneity. However, the limited forecast horizon is not suitable for large systems, requiring specific solutions to control the system for horizons beyond the forecasts horizons.

Wet weather - exceeding design capacity. The warning systems described by Einfalt et al. (2016), and Meneses et al. (2015) focus on extreme rain events, when the magnitude of the rain event is expected to exceed the capacity of any control strategy. In this domain, it is essential to obtain a good accuracy in predicting the weather status (normal rain/cloudburst) in order to minimize false alarms. Also, a high spatial resolution is necessary to forecast flooding events, which tend to occur at small scales. Depending on the type of warning system, spatial resolution can be high or low, as well as the needed forecast horizon can be short (e.g. detailed flooding maps to direct rescue efforts) or long. In fact, systems aiming at alerting authorities on potential risks require long forecast horizons and low spatial accuracy (*"tomorrow there is a flooding risk in that area of the city"*), while systems aiming at supporting rescue operation and minimizing damages require high spatial accuracy while short time horizons are sufficient ("*there is a flooding risk in that street in the next hour, so send the firemen there"*

Based on these considerations, the domain-based framework can be schematized as in Figure 1. The suggested forecast horizon decreases from days-weeks to minute-hours when moving from the dry to the wet operational domain. Similarly, the needed volume accuracy increases from dry (where only information on the future state of the system is needed) to wet domains. The highest volume accuracy is needed by the *wet – exceeding design capacity* domain (if the system aims at proving flooding maps), or by the *wet* domain. For example, Lovring (2016) compared different forecast products applied to the Copenhagen flood warning system (Meneses et al., 2015), showing how the volume accuracy affected the quality of the forecasted flooding maps.

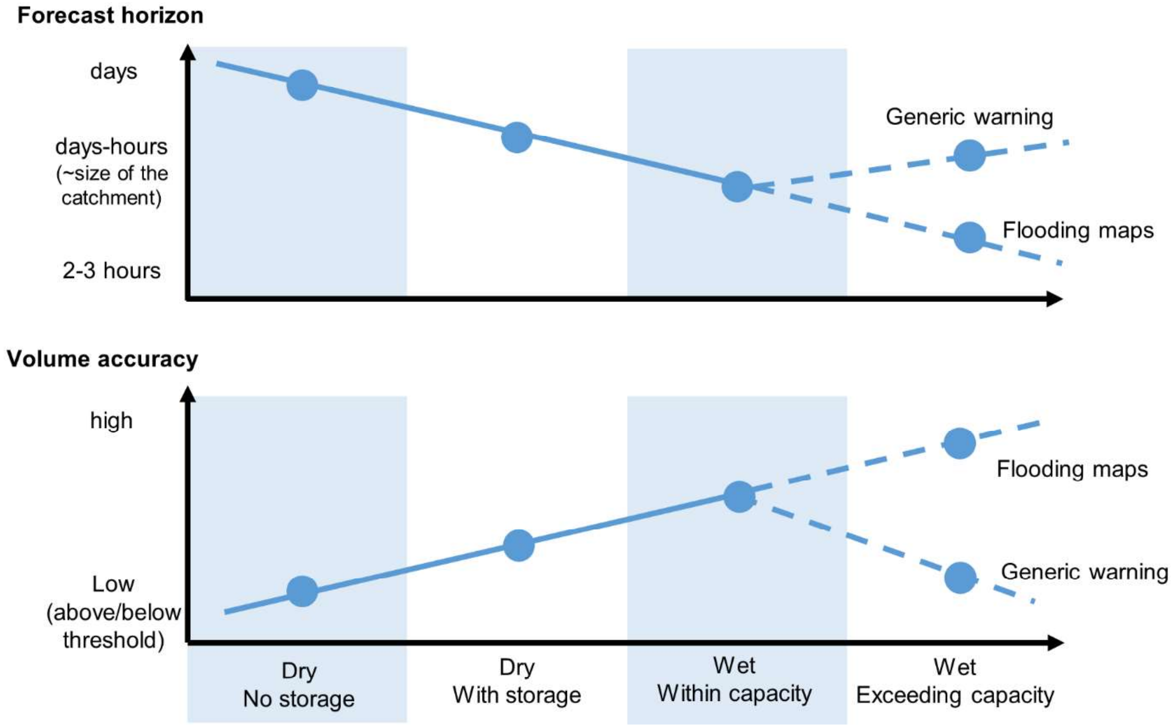

Figure 1. Schematic representation of framework for classifying rainfall forecasts based on operational domains.

Challenges and future developments

Methods for forecasting rainfall are in a continuous evolution: spatial and temporal resolutions are becoming smaller, with rainfall predicted on grids with a scale smaller than urban catchments at more frequent intervals (minutes-hourly). New forecast products are being developed, merging existing techniques (e.g. NWP with assimilated radar measurements). Control strategies can now benefit from forecast products ranging from short (minutes) to long (weeks) horizons and from a few hundreds of meters to several kilometres spatial resolution. However, it is important to communicate to operators that these forecasts have different skills, which make them more suitable for different operational domains. For example, NWP could be tuned to show great accuracy on extreme events on a scale greater than the urban catchment (see e.g. Lovring, 2016), making this forecast more suitable for warning, rather than for control. The comparison presented by ForecastWatch (2016), for example, evaluated forecasts skills based on typical meteorological parameters (temperature, daily precipitation). Similar comparison should be performed with focus on the temporal and spatial scales needed by applications in integrated urban wastewater systems.

The proposed framework can help final users to better understand their needs and to select the most appropriate forecast (“*which forecast product should I use for my MPC”*).

Also, the framework can be used to distinguish between different operational domains based on the analysis of rainfall forecasts, thereby enabling operators to switch between different control strategies according to the expected domain (“*which MPC strategy should I run based on the expected state of my system?”* – e.g. Figure 2*)*. Existing examples of MPC strategies merge different operational domains in the same objective function: Vezzaro and Grum (2014), for example, utilize the same strategy for both *dry weather with stored runoff* and *wet weather within the capacity*.

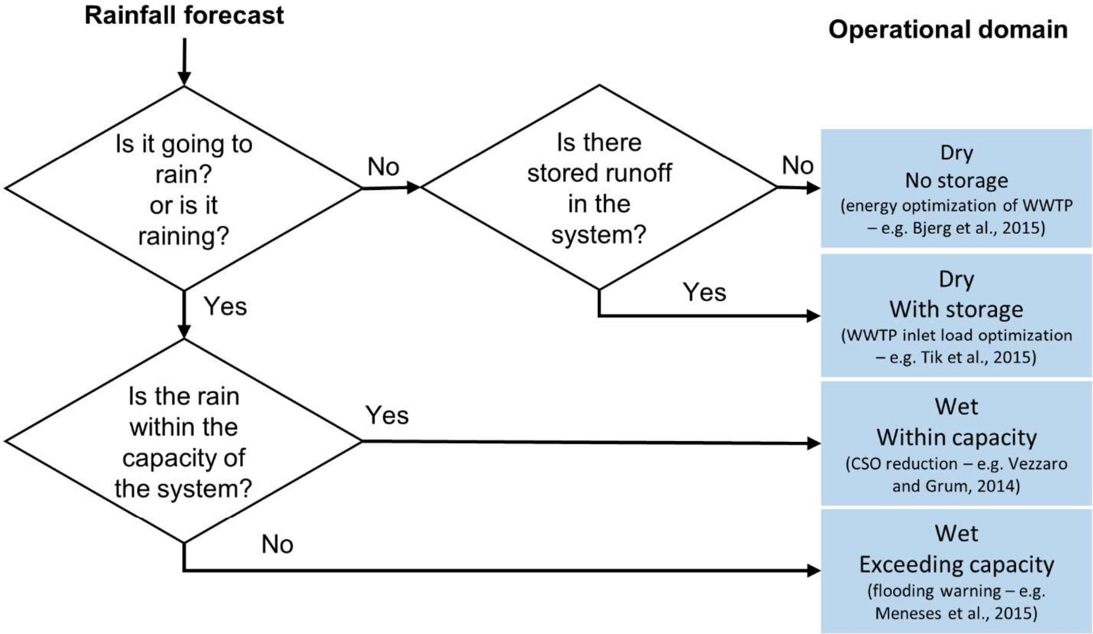

Figure 2. Theoretical example on how rainfall forecasts can be coupled to different control strategies can operate on different domains.

However, an alternative approach might define an optimal strategy for each operational domain~~s~~, with a switching function driven by rainfall forecasts to define the optimal control strategy to be actuated (e.g. Figure 2). Within the Water Smart Cities project, the available forecasts will be evaluated for different operational domains, with focus on their accuracy, precision and uncertainty and their usage for control of integrated urban wastewater systems.

Uncertainty plays an essential role in a successful implementation of MPC strategies. Communicating forecast uncertainty to operators in a clear and easily understandable manner is the key factor which builds operators' trust in the control strategy and increases their confidence in the optimal set points defined by the MPC (as in the example shown in Figure 3).The methodology proposed by Courdent et al. (2016b), for example, provides an economic framework to analyse forecasts uncertainty.

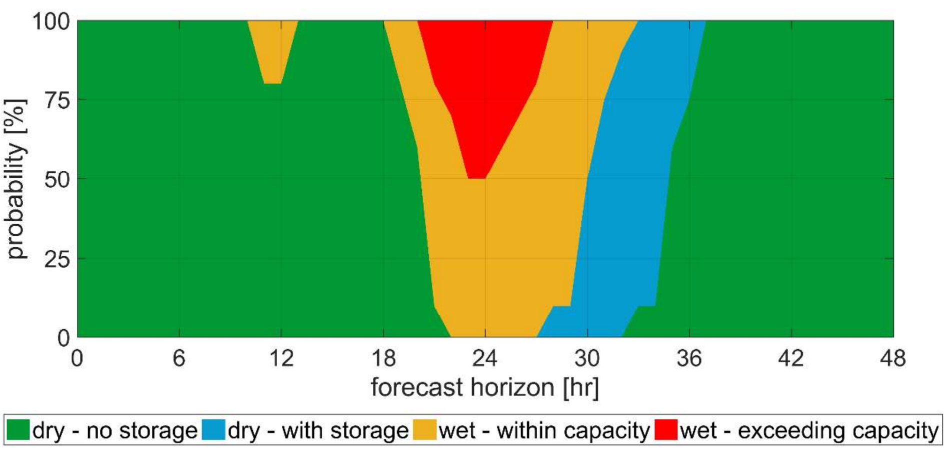

Figure 3. A possible visualization of forecast uncertainty of operational domains for operators.

CONCLUSIONS

The proposed framework identifies four different *operational domains,* which can be used to describe and classify different MPC strategies and rainfall forecast methods. The operational domains can help operators to navigate across the wide choice of control strategies and forecast products by (a) classifying the existing options for optimization of their systems in terms of different operational domains (*which control strategy should I use to solve my problem?*), and (b) identifying the most appropriate rainfall forecast for the intended use (*which type of rainfall forecast is most suitable for my control?*).

Given the continuous evolution in the field of rainfall forecasts, and the on-going research activities, this study provides a starting point for communicating the potential of MPC in optimizing integrated urban wastewater systems to a wider, not specialised, audience and thereby helping to spread the implementation of these methods.

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